

CLAIMS

We claim:

1. A method of fabricating a waveguide in ferroelectric crystals, comprising the steps of:

providing a ferroelectric crystal;

diffusing a vapor phase proton into the ferroelectric crystal by a vapor 5 proton-exchange process to form a vapor proton-exchange (VPE) waveguide material structure having a step refractive index profile; and

treating the VPE waveguide material structure with one or more processes selected from the group consisting of: a post thermal anneal process and an additional reverse proton-exchange process to complete fabrication of the 10 waveguide,

whereby the refractive index profile of the fabricated waveguide can be flexibly optimized.

2. The method of claim 1, wherein the ferroelectric crystal is selected from the group consisting of: lithium niobate ( $\text{LiNbO}_3$ ), lithium tantalate ( $\text{LiTaO}_3$ ),  $\text{KTiOPO}_4$  (KTP),  $\text{KNbO}_3$ , KDP and their family such as  $\text{MgO:LiNbO}_3$ ,  $\text{ZnO:LiNbO}_3$ , periodically poled KTP (PP-KTP) periodically poled lithium niobate (PP-LN) or periodically poled lithium tantalate (PP-LT).

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3. The method of claim 1, wherein the ferroelectric crystal is selected from the group consisting of: congruent LiNbO<sub>3</sub>(CLN) and stoichiometric LiNbO<sub>3</sub>(SLN); the above crystals with doping such as MgO:CLN, ZnO:CLN, MgO:SLN, ZnO:SLN; the above crystals at different crystal orientations including X-cut, Y-cut or Z-cut; and the above crystals with periodic or aperiodic ferroelectric domain reversals in their crystal bodies.
4. The method of claim 1, wherein the ferroelectric crystal is a LiNbO<sub>3</sub> or a LiTaO<sub>3</sub> ferroelectric crystal and their respective families.
5. The method of claim 1, wherein the ferroelectric crystal is a LiNbO<sub>3</sub> ferroelectric crystal and its family.
6. The method of claim 1, wherein the ferroelectric crystal has a crystal orientation selected from the group consisting of: X-cut, Y-cut or Z-cut.
7. The method of claim 1, wherein the vapor proton-exchange process is conducted in a vapor selected from the group consisting of: pure acid vapor and buffering/dilute acid vapor.
8. The method of claim 1, wherein the vapor proton-exchange process is conducted in a vapor selected from the group consisting of: pure benzoic acid vapor; pure stearic acid vapor; and pure pyrophosphoric acid vapor.

9. The method of claim 1, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>,

10. The method of claim 1, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $2*10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

11. The method of claim 1, wherein the vapor phase proton has a source selected from the group consisting of benzoic acid, stearic acid, and pyrophosphoric acid.

12. The method of claim 1, wherein the vapor phase proton is benzoic acid and its family.

13. The method of claim 1, wherein the post thermal anneal process is conducted at the following conditions:

temperature: from about 250 to 400°C; and

time: from about 1 to 72 hours.

14. The method of claim 1, wherein the post thermal anneal process is conducted at the following conditions:

temperature: from about 300 to 360°C; and

time: from about 1 to 36 hours.

15. The method of claim 1, wherein the additional reverse proton-exchange process is conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 72 hours; wherein the LiNO<sub>3</sub> concentration is from about 30 to 45 mol. %, the KNO<sub>3</sub> concentration is from about 30 to 60 mol. % and the NaNO<sub>3</sub> concentration is from about 10 to 30 mol. %.

16. The method of claim 1, wherein the additional reverse proton-exchange process is conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 36 hours; wherein the LiNO<sub>3</sub> concentration is from about 35 to 40 mol. %, the KNO<sub>3</sub> concentration is from about 40 to 50 mol. % and the NaNO<sub>3</sub> concentration is from about 15 to 25 mol. %.

17. The method of claim 1, wherein the fabricated waveguide may be used in the following process applications:

quasi-phase matching waveguides and nonlinear guided wave applications such as: second harmonic generation; sum frequency generator difference frequency generation; wavelength converters; dispersion compensation elements; nonlinear compensation elements; optical parametric frequency amplification and generation; cascaded nonlinear frequency conversion; light source for laser display, laser scanner, laser printing, laser spectroscopic, sensing and detection; optical frequency mixers for optical fiber communication and optical signal processing;

electro-optics applications and their optimizations such as electro-optics amplitude, phase modulators or high-speed modulators;

acoustic optics applications and optimization; and

integrated optics and waveguide coupling optimization.

18. The method of claim 1, wherein the VPE waveguide material structure is treated with only a post thermal anneal process.

19. The method of claim 1, wherein the VPE waveguide material structure is treated with a post thermal anneal process and then an additional reverse proton-exchange process.

20. The method of claim 1, wherein the VPE waveguide material structure is treated only with an additional reverse proton-exchange process.

21. The method of claim 1, wherein the VPE waveguide material structure is treated with an additional reverse proton-exchange process and then a post thermal anneal process.

22. The method of claim 1, wherein the fabricated waveguide is a multi-layer waveguide structure formed by treating the VPE waveguide with a reverse proton-exchange process and then with at least one more additional sets of:

- a) vapor phase proton exchange process followed by a further
- b)reverse proton-exchange process.

23. The method of claim 1, wherein the fabricated waveguide is treated with one or more of the following sequence of processes:

a post thermal anneal process;

a post thermal anneal process followed by an additional reverse proton-exchange process;

an additional reverse proton-exchange process; and

an additional reverse proton-exchange process followed by a post thermal anneal process.

24. The method of claim 1, wherein the fabricated waveguide is a dispersion shifting waveguide.

25. The method of claim 1, wherein the fabricated waveguide is a dispersion flattened waveguide.

26. The method of claim 1, wherein the fabricated waveguide is simultaneously formed with an optimized waveguide width and depth profile.

27. The method of claim 1, wherein the fabricated waveguide is simultaneously formed with an optimized waveguide width and depth profile wherein the fabricated waveguide has a very high process tolerance.

28. The method of claim 1, wherein the fabricated waveguide is simultaneously formed with an optimized waveguide width and depth profile wherein the fabricated waveguide is less sensitive to: channel width variations; process temperature uniformity and temperature stability.

29. The method of claim 1, wherein the fabricated waveguide may be used in the following process applications:

dispersion shifting waveguides, dispersion flattened waveguides, efficiency enhancement for quasi-phase matching waveguides, nonlinear guided wave applications, integrated optics and waveguide optimization applications.

30. A method of fabricating a waveguide in ferroelectric crystals, comprising the steps of:

providing a ferroelectric crystal;  
diffusing a vapor phase proton into the ferroelectric crystal by a vapor proton-exchange process to form a vapor proton-exchange (VPE) waveguide material structure having a step refractive index profile; and

treating the VPE waveguide material structure with a post thermal anneal to complete fabrication of the waveguide,  
whereby the refractive index profile of the fabricated waveguide can be flexibly optimized.

31. The method of claim 30, wherein the ferroelectric crystal is selected from the group consisting of: lithium niobate ( $\text{LiNbO}_3$ ), lithium tantalate ( $\text{LiTaO}_3$ ),  $\text{KTiOPO}_4$  (KTP),  $\text{KNbO}_3$ , KDP and their family such as  $\text{MgO:LiNbO}_3$ ,  $\text{ZnO:LiNbO}_3$ , periodically poled KTP (PP-KTP) periodically poled lithium niobate (PP-LN) or periodically poled lithium tantalate (PP-LT).

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32. The method of claim 30, wherein the vapor proton-exchange process is conducted in a vapor selected from the group consisting of: pure acid vapor and buffering/dilute acid vapor.

33. The method of claim 30, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

34. The method of claim 30, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $2*10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

35. The method of claim 30, wherein the vapor phase proton is benzoic acid and its family.

36. The method of claim 30, wherein the post thermal anneal process is conducted at the following conditions:

temperature: from about 250 to 400°C; and

time: from about 1 to 72 hours.

37. The method of claim 30, wherein the post thermal anneal process is conducted at the following conditions:

temperature: from about 300 to 360°C; and

time: from about 1 to 36 hours.

38. A method of fabricating a waveguide in ferroelectric crystals, comprising the steps of:

- providing a ferroelectric crystal;
- diffusing a vapor phase proton into the ferroelectric crystal by a vapor 5 proton-exchange process to form a vapor proton-exchange (VPE) waveguide material structure having a step refractive index profile; and
- treating the VPE waveguide material structure with a post thermal anneal and then an additional reverse proton-exchange process to complete fabrication of the waveguide,
- 10 whereby the refractive index profile of the fabricated waveguide can be flexibly optimized.

39. The method of claim 38, wherein the ferroelectric crystal is selected from the group consisting of: lithium niobate ( $\text{LiNbO}_3$ ), lithium tantalate ( $\text{LiTaO}_3$ ),  $\text{KTiOPO}_4$  (KTP),  $\text{KNbO}_3$ , KDP and their family such as  $\text{MgO:LiNbO}_3$ ,  $\text{ZnO:LiNbO}_3$ , periodically poled KTP (PP-KTP) periodically poled lithium niobate (PP-LN) or periodically poled lithium tantalate (PP-LT).

40. The method of claim 38, wherein the vapor proton-exchange process is conducted in a vapor selected from the group consisting of: pure acid vapor and buffering/dilute acid vapor.

41. The method of claim 38, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

42. The method of claim 38, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $2*10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

43. The method of claim 38, wherein the vapor phase proton is benzoic acid and its family.

44. The method of claim 38, wherein the post thermal anneal process conducted at the following conditions:

temperature: from about 250 to 400°C; and

time: from about 1 to 72 hours; and

the additional reverse proton-exchange process conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 72 hours; wherein the LiNO<sub>3</sub> concentration is from about 30 to 45 mol. %, the KNO<sub>3</sub> concentration is from about 30 to 60 mol. % and the NaNO<sub>3</sub> concentration is from about 10 to 30 mol. %.

45. The method of claim 38, wherein the post thermal anneal process conducted at the following conditions:

temperature: from about 300 to 360°C; and

time: from about 1 to 36 hours; and

the additional reverse proton-exchange process conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 36 hours; wherein the LiNO<sub>3</sub> concentration is from about 35 to 40 mol. %, the KNO<sub>3</sub> concentration is from about 40 to 50 mol. % and the NaNO<sub>3</sub> concentration is from about 15 to 25 mol. %.

46. A method of fabricating a waveguide in ferroelectric crystals, comprising the steps of:

5 providing a ferroelectric crystal;  
diffusing a vapor phase proton into the ferroelectric crystal by a vapor proton-exchange process to form a vapor proton-exchange (VPE) waveguide material structure having a step refractive index profile; and

10 treating the VPE waveguide material structure with only an additional reverse proton-exchange process to complete fabrication of the waveguide, whereby the refractive index profile of the fabricated waveguide can be flexibly optimized.

47. The method of claim 46, wherein the ferroelectric crystal is selected from the group consisting of: lithium niobate (LiNbO<sub>3</sub>), lithium tantalate (LiTaO<sub>3</sub>), KTiOPO<sub>4</sub> (KTP), KNbO<sub>3</sub>, KDP and their family such as MgO:LiNbO<sub>3</sub>, ZnO:LiNbO<sub>3</sub>, periodically poled KTP (PP-KTP) periodically poled lithium niobate (PP-LN) or periodically poled lithium tantalate (PP-LT).

48. The method of claim 46, wherein the vapor proton-exchange process is conducted in a vapor selected from the group consisting of: pure acid vapor and buffering/dilute acid vapor.

49. The method of claim 46, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

50. The method of claim 46, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $2*10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

51. The method of claim 46, wherein the vapor phase proton benzoic acid and its family.

52. The method of claim 46, wherein the additional reverse proton-exchange process conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 72 hours; wherein the LiNO<sub>3</sub> concentration is from about 30 to 45 mol. %, the KNO<sub>3</sub> concentration is from about 30 to 60 mol. % and the NaNO<sub>3</sub> concentration is from about 10 to 30 mol. %.

53. The method of claim 46, wherein the additional reverse proton-exchange process conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 36 hours; wherein the LiNO<sub>3</sub> concentration

is from about 35 to 40 mol. %, the  $\text{KNO}_3$  concentration is from about 40 to 50 mol. % and the  $\text{NaNO}_3$  concentration is from about 15 to 25 mol. %.

54. A method of fabricating a waveguide in ferroelectric crystals, comprising the steps of:

providing a ferroelectric crystal;

diffusing a vapor phase proton into the ferroelectric crystal by a vapor

5 proton-exchange process to form a vapor proton-exchange (VPE) waveguide material structure having a step refractive index profile; and

treating the VPE waveguide material structure with an additional reverse proton-exchange process and then a post thermal anneal to complete fabrication of the waveguide,

10 whereby the refractive index profile of the fabricated waveguide can be flexibly optimized.

55. The method of claim 54, wherein the ferroelectric crystal is selected from the group consisting of: lithium niobate ( $\text{LiNbO}_3$ ), lithium tantalate ( $\text{LiTaO}_3$ ),  $\text{KTiOPO}_4$  (KTP),  $\text{KNbO}_3$ , KDP and their family such as  $\text{MgO:LiNbO}_3$ ,  $\text{ZnO:LiNbO}_3$ , periodically poled KTP (PP-KTP) periodically poled lithium niobate (PP-LN) or periodically poled lithium tantalate (PP-LT).

56. The method of claim 54, wherein the vapor proton-exchange process is conducted in a vapor selected from the group consisting of: pure acid vapor and buffering/dilute acid vapor.

57. The method of claim 54, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

58. The method of claim 54, wherein the vapor proton-exchange (VPE) waveguide material structure has an adjusted proton concentration of from about  $2*10^{21}$  to  $2*10^{22}$  atoms/cm<sup>3</sup>.

59. The method of claim 54, wherein the vapor phase proton is benzoic acid and its family.

60. The method of claim 54, wherein the additional reverse proton-exchange process is conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 72 hours; wherein the LiNO<sub>3</sub> concentration is from about 30 to 45 mol. %, the KNO<sub>3</sub> concentration is from about 30 to 60 mol. % and the NaNO<sub>3</sub> concentration is from about 10 to 30 mol. %; and the post thermal anneal process is conducted at the following conditions:

temperature: from about 250 to 400°C; and

time: from about 1 to 72 hours.

61. The method of claim 54, wherein the additional reverse proton-exchange process is conducted in a mixture of LiNO<sub>3</sub>-KNO<sub>3</sub>-NaNO<sub>3</sub> at a temperature of from about 200 to 400°C for from about 1 to 36 hours; wherein the LiNO<sub>3</sub> concentration

is from about 35 to 40 mol. %, the  $\text{KNO}_3$  concentration is from about 40 to 50 mol. % and the  $\text{NaNO}_3$  concentration is from about 15 to 25 mol. %.; and the post thermal anneal process is conducted at the following conditions: temperature: from about 300 to 360°C; and time: from about 1 to 36 hours.

100-200-300-400-500-600-700-800-900